UDC 666.1.038.3

PROPERTIES OF GLASS SUBJECTED TO COMPLEX THERMAL TREATMENT

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Translated from Steklo i Keramika, No. 5, pp. 8 – 10, May, 2004.

A function describing the properties of glass subjected to complex thermal treatment is proposed. The advantages of three-stage thermal treatment before pulse hardening are specified.

The use of the well-known methods of thermal treatment of glass (hardening and annealing) cannot satisfy all requirements imposed on the properties of glass articles needed by the consumer. Thus, when annealed glass is used in the production of triplex glass, the thickness of the product cannot be decreased because of its low strength, whereas hardened glass cannot be applied in triplex due to its self-sustained type of destruction and high fragmentation. Complex thermal treatment (CTT) is the only currently known method imparting to the end product the properties of both annealed glass (fracturing into large fragments that do not obstruct the driver's vision in a car accident) and hardened glass, i.e., high strength, which makes it possible to reduce the thickness of triplex glass (USSR Inventor's Certif. No. 2151750).

The first step in this line of research is pulse hardening, which implies heating of glass to the hardening temperature and intense cooling by natural convection with a subsequent exposure (Fig. 1*a*). The disadvantage of this method is its substantial duration, which can be shortened by introducing a third additional stage of cooling (Fig. 1*b*).

Glass subjected to CTT differs from hardened glass in several properties, primarily, in the form of their inner hardening stress curves and the values of these stresses (USSR Inventor's Certif. No. 2151750) [1]. To describe the specified properties, the parameter χ was selected, which was named the curve quality coefficient and represented the ratio of the absolute values of the surface σ_s and central σ_c stresses:

$$\chi = \left| \frac{\sigma_s}{\sigma_c} \right| .$$

The algorithms for the calculation of residual surface and central stresses in CTT-treated glass is given in [2]; however, it is rather cumbersome, which complicates its use by practicing engineers. It is necessary to identify a function that could adequately describe glass properties after CTT and would be sufficiently simple. Such dependence was found by the authors in the course of the machine experiment:

$$\chi\,(d, t\,(0), \alpha_1, \alpha_2, \tau_1, \tau_2) = 2.2 + a_1 \exp\left[-\left(\frac{\tau_1 / \tau_2 - a_2}{a_3} \right)^2 \right],$$

where d is the glass thickness; $t\,(0)$ is the initial glass temperature; τ_1 is the duration of the first cooling stage; τ_2 is the exposure duration in the conditions of natural convection.

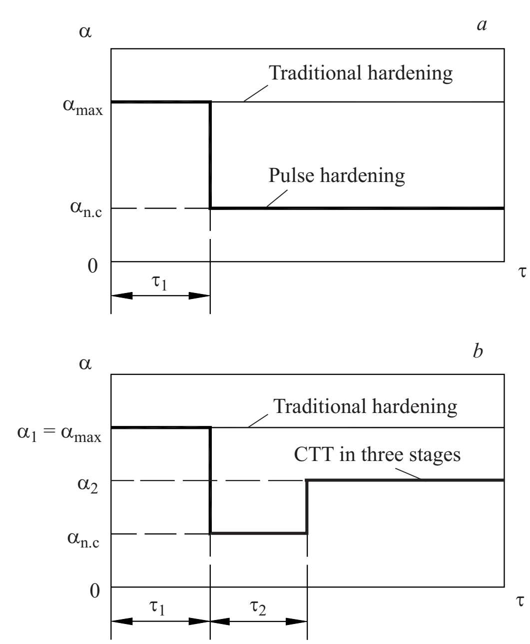

Fig. 1. Principal schemes of complex thermal treatment: *a*) *pulse hardening*: α_{max} and $\alpha_{n.c}$ are the heat transfer coefficients of the first cooling stage and natural convection, respectively, τ_1) the duration of the first stage of cooling; *b*) *three-stage scheme*: α_1 and α_2) heat transfer coefficients of the first and the last cooling stages, respectively; τ_2) duration of the second cooling stage (natural convection).

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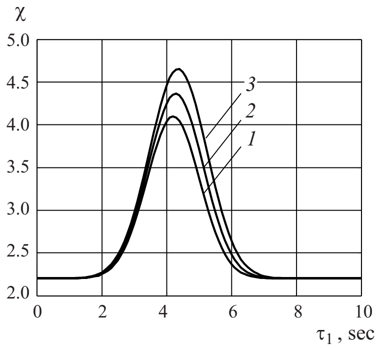

Fig. 2. Dependence of the quality coefficient χ on the time span τ_1 for $d = 6$ mm, $\alpha_1 = 450$ W/(m$^2 \cdot$ K), $\alpha_2 = 450$ W/(m$^2 \cdot$ K): *1*, *2*, and *3*) $t(0) = 620$, 650, and 680°C, respectively.

The coefficients a_1, a_2, and a_3, in turn, are functions of the glass thickness, initial glass temperature, and the heat transfer coefficient of the first and the last stage of intense cooling.

Thus, the expression obtained makes it possible to investigate the properties of glass subjected to CTT without using the algorithm.

It is known that the presence of low residual central stresses in glass allows for its machine treatment (cutting, drilling) without destroying the article, whereas high residual surface stresses ensure sufficient strength of glass [2], which corresponds to the maximum in the function of the dependence of the quality coefficient on the heat treatment parameters, which has an extremal form. This function makes it possible to perform the qualitative and quantitative evaluation of the properties of glass subjected to three-stage thermal treatment and issue recommendations for developing complicated thermal treatment regimes to be used by practicing engineers.

The growth of such parameters as the initial hardening temperature and the glass thickness, as well as a decrease in the intensity of the first and second cooling stages, lead to an increased duration of the first stage of thermal treatment required to reach the maximum in the function $\chi(d, t(0), \alpha_1, \alpha_2, \tau_1, \tau_2)$.

The dependence $\chi(\tau_1)$ on variation of the initial temperature, other conditions being equal, is shown in Fig. 2. It can be seen that the value of the curve quality function in the extremum point grows with an increasing hardening temperature.

It should be noted that in the Author's Certificate (USSR Inventor's Certif. No. 2151750) the duration of the first stage of intense cooling is limited to 3 sec; however, the research performed has revealed that it can actually reach 10 sec.

The effect of the glass thickness on the curve quality function is shown in Fig. 3. With increasing glass thickness (to reach the maximum quality coefficient) it is necessary to increase the duration of the first cooling phase. A decrease in the glass thickness increases the quality coefficient at the points corresponding to the extremum.

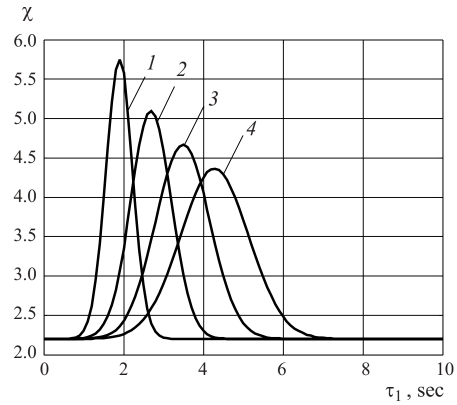

Fig. 3. Dependence of the quality coefficient χ on the time span τ_1 at $t(0) = 650$°C, $\alpha_1 = 450$ W/(m$^2 \cdot$ K), $\alpha_2 = 450$ W/(m$^2 \cdot$ K): *1*, *2*, *3*, and *4*) $d = 3$, 4, 5, and 6 mm, respectively.

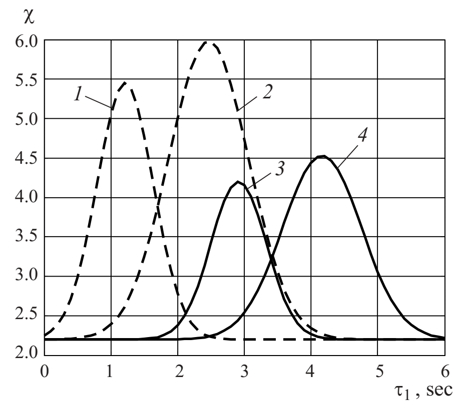

Fig. 4. Dependence of the quality coefficient χ on the time span τ_1 for $d = 4$ mm, $t(0) = 650$°C: *1*) $\alpha_1 = 700$ W/(m$^2 \cdot$ K), $\alpha_2 = 700$ W/(m$^2 \cdot$ K); *2*) $\alpha_1 = 700$ W/(m$^2 \cdot$ K), $\alpha_2 = 200$ W/(m$^2 \cdot$ K); *3*) $\alpha_1 = 200$ W/(m$^2 \cdot$ K), $\alpha_2 = 700$ W/(m$^2 \cdot$ K); *4*) $\alpha_1 = 200$ W/(m$^2 \cdot$ K), $\alpha_2 = 200$ W/(m$^2 \cdot$ K).

The effect of glass cooling intensity on the function of the stress curve quality is shown in Fig. 4. A decrease in cooling intensity, other conditions being equal, has an effect on the shift in the function extremum along the axis τ_1, since the rate of reaching the vitrification interval, in which residual hardening stresses are formed, decreases. Furthermore, as the blowing intensity at the first cooling stage decreases, other thermal treatment parameters being equal, the quality coefficient function reaches higher values at points corresponding to the extremum. A decrease in the cooling intensity α_2, other conditions being equal, affects the shift of the function extremum along the axis τ_1 with a simultaneous increase in the value of this function at the point corresponding to its maximum.

The study of the degree of the joint effect of heat transfer coefficient α_1 and α_2 on the properties of sheet glass subjected to CTT revealed the following regularity: an increase in the cooling intensity at the first stage and its decrease at

TABLE 1

Glass-hardening regimes (for pulse hardening $\alpha_2 = \alpha^*_{n.c}$)	Strength, MPa		Quality coefficient		Process duration, sec	
	pulse hardening	three-stage CTT	pulse hardening	three-stage CTT	pulse hardening**	three-stage CTT***
d = 6 mm t(0) = 680 °C α_1 = 450 W/(m^2 · K) α_2 = 450 W/(m^2 · K) τ_1 = 6 sec τ_2 = 60 sec	180	180	2.9	2.9	600	100
d = 3 mm t(0) = 620 °C α_1 = 700 W/(m^2 · K) α_2 = 700 W/(m^2 · K) τ_1 = 1 sec τ_2 = 30 sec	152	152	4.3	4.3	600	50

* $\alpha_{n.c}$ is the heat transfer coefficient corresponding to natural convection, $\alpha_{n.c}$ = 12 – 30 W/(m^2 · K).

** Process duration is taken from [2].

*** Process duration is calculated using the algorithm in [1].

the second stage provides for the highest quality coefficient value.

The effect of τ_1 and τ_2 on the quality coefficient was studied as well. The following specifics were revealed, which have to be taken into account in developing a technological regimes:

– a decrease in glass exposure under natural convection decreases the quality coefficient to 2.2, which corresponds to normal hardening of glass;

– an increase in the duration of glass exposure under natural convection makes it possible to reach the maximum value of the quality coefficient; however, the duration of the CTT process increases, which is undesirable.

The optimum values of τ_2 is calculated based on the specified formula.

It can be seen from the data in Table 1 that the duration of pulse hardening exceeds the duration of the three-stage thermal treatment by 6 – 12 times, and the use of either regime ensures the production of glass with equal quality coefficients and equal strength.

Thus, the use of the proposed algorithm makes it possible to give a qualitative and quantitative evaluation of the properties of glass subjected to CTT and design technological regimes without using the cumbersome algorithm given in [1]. The results of these studies can be used in designing technological regimes for strengthening sheet glass.

REFERENCES

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